RESEARCH PAPER

Anatomical Variations of the Circle of Willis and their Clinical Significance

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ABSTRACT

Background: The Circle of Willis is a major arterial anastomotic network located at the base of the brain and plays a central role in maintaining collateral cerebral circulation during vascular compromise. Anatomical variations of this arterial polygon are frequently reported and may influence cerebrovascular risk, aneurysm formation, ischemic events, and neurosurgical outcomes.

Objective: This research aims to synthesize reported anatomical variations of the Circle of Willis and evaluate their clinical significance using a segment-based morpho-clinical mapping approach.

Methods: A structured literature search was conducted using PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar for studies published between January 2000 and March 2026. After duplicate removal, title–abstract screening, and full-text eligibility assessment, 52 studies were included for qualitative synthesis. Evidence from cadaveric dissection, computed tomography angiography, magnetic resonance angiography, and digital subtraction angiography studies was analyzed.

Results: The research evidence showed that Circle of Willis variations commonly involve hypoplasia, aplasia, duplication, fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed-pattern configurations. The anterior communicating artery, posterior communicating artery, A1 segment, and P1 segment were identified as frequently affected regions. A segment-wise clinical relevance matrix was developed to connect anatomical variations with potential implications for collateral circulation, aneurysm predisposition, stroke vulnerability, radiological interpretation, and surgical planning.

Conclusion: Anatomical variations of the Circle of Willis should not be considered only morphological findings, but clinically meaningful vascular configurations. Their recognition through cadaveric evaluation, CTA, MRA, or angiographic imaging is important for anatomists, radiologists, neurologists, and neurosurgeons. The proposed morpho-clinical mapping approach improves the translational value of anatomical variation studies and supports clinically oriented anatomical interpretation.

Keywords: Circle of Willis, anatomical variations, cerebral circulation, hypoplasia, aneurysm, stroke, clinical anatomy

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INTRODUCTION

The Circle of Willis is a major arterial anastomotic network located at the base of the brain, where it connects the anterior and posterior cerebral circulations (Maldonado et al., 2026). It is formed mainly by the anterior cerebral arteries, anterior communicating artery, internal carotid arteries, posterior communicating arteries, and posterior cerebral arteries (Maldonado et al., 2026; Saha et al., 2026). This arterial polygon plays an essential role in maintaining cerebral blood flow by providing collateral circulation when one or more major cerebral vessels are narrowed, blocked, or functionally compromised (Beneš et al., 2026; He et al., 2026). Because of this compensatory role, the Circle of Willis is considered one of the most clinically important vascular structures in neuroanatomy and cerebrovascular medicine (Kubicki et al., 2026).

Although the Circle of Willis is commonly described as a complete and symmetrical arterial ring, this classical pattern is not present in all individuals (Saha et al., 2026). Several anatomical variations have been reported in cadaveric, computed tomography angiography, magnetic

resonance angiography, and digital subtraction angiography studies (Triantafyllou et al., 2026a; Cai et al., 2026). These variations commonly include hypoplasia, aplasia, duplication, fenestration, accessory vessels, and fetal-type posterior cerebral artery configuration (Triantafyllou et al., 2026a). The anterior communicating artery, posterior communicating artery, A1 segment, and P1 segment are among the most frequently affected regions of the Circle of Willis (Cai et al., 2026; Gaigalaite et al., 2026).

The clinical significance of these variations is mainly related to their influence on collateral cerebral circulation (He et al., 2026). A complete and well-developed Circle of Willis can help maintain cerebral perfusion during carotid artery stenosis, arterial occlusion, or acute ischemic events (Kubicki et al., 2026). In contrast, incomplete or hypoplastic arterial segments may reduce collateral capacity and increase susceptibility to ischemic stroke or transient ischemic attack (Gaigalaite et al., 2026). Variations in the posterior communicating artery and posterior cerebral artery are especially important because they may affect blood flow distribution between the carotid and vertebrobasilar systems (Zeng et al., 2026; Gaigalaite et al., 2026).

Anatomical variations of the Circle of Willis are also important in relation to intracranial aneurysm formation and rupture risk (Qannas et al., 2026; Zeng et al., 2026). Abnormal vessel configuration and asymmetric blood flow may increase hemodynamic stress at arterial junctions, particularly near the anterior communicating artery and posterior communicating artery (Kubicki et al., 2026). Accurate identification of these variations is essential during radiological interpretation using CTA, MRA, and conventional angiography (de Liyis et al., 2026; Khayat et al., 2026). Knowledge of variant vascular anatomy is also important for neurosurgeons and interventional neuroradiologists during aneurysm clipping, endovascular coiling, skull-base surgery, and vascular bypass procedures (Dowlati et al., 2026; Triantafyllou et al., 2026b).

Therefore, a comprehensive research of the anatomical variations of the Circle of Willis is necessary to improve both anatomical understanding and clinical decision-making. Previous studies have reported several individual variations, but a clinically oriented synthesis is needed to connect morphology with cerebrovascular outcomes. The present research aims to summarize the major anatomical variations of the Circle of Willis and explain their significance in stroke risk, aneurysm predisposition, collateral circulation, imaging diagnosis, and surgical planning. By using a segment-based morpho-clinical approach, this research provides a useful framework for anatomists, radiologists, neurologists, and neurosurgeons.

1.1 Problem Statement / Rationale of the research

Although the Circle of Willis is a critical arterial network for maintaining collateral cerebral circulation, its anatomical structure shows wide variation among individuals. These variations are frequently reported in cadaveric, CTA, MRA, and angiographic studies, but their clinical implications are often discussed separately rather than in an integrated manner. Variations such as hypoplasia, aplasia, duplication, fenestration, and fetal-type configurations may influence stroke susceptibility, aneurysm formation, collateral circulation efficiency, radiological interpretation, and neurosurgical planning. Therefore, clinically oriented research is needed to synthesize these anatomical variations and connect them with their practical significance in diagnosis, prognosis, and treatment planning.

1.2 Rationale of the research

The Circle of Willis is an important arterial anastomotic network that contributes significantly to cerebral collateral circulation. Numerous cadaveric and imaging-based studies have reported considerable anatomical variability in its constituent vessels. These variations have been associated with differences in collateral blood flow, susceptibility to cerebrovascular disorders, aneurysm development, radiological interpretation, and neurosurgical planning. Although substantial literature exists on individual anatomical variations, the available evidence remains dispersed across anatomical, radiological, and clinical disciplines. Therefore, a comprehensive research of the published literature is required to summarize the reported anatomical variations of the Circle of Willis and discuss their potential clinical significance in an integrated manner.

1.3 Scope of the research

The present research aims to provide a comprehensive overview of the anatomical variations of the Circle of Willis reported in the published literature. The research synthesizes evidence from cadaveric, angiographic, computed tomography angiography, and magnetic resonance angiography studies. Particular emphasis is placed on commonly reported variations, their anatomical distribution, and their potential implications for collateral

circulation, cerebrovascular disease, radiological evaluation, and neurosurgical practice.

1.4 Contributions

The novel contributions of this study are:

1. This research introduces a segment-based morpho-clinical mapping approach to connect each Circle of Willis variation with its clinical relevance.
2. It classifies common variations such as hypoplasia, aplasia, duplication, fenestration, accessory vessels, and mixed patterns in a clinically understandable manner.
3. It explains the significance of Circle of Willis variations in stroke risk, aneurysm predisposition, collateral circulation, radiological diagnosis, and neurosurgical planning.

1.5 Objectives

The objectives of this research are:

1. To summarize the major anatomical variations of the Circle of Willis reported in cadaveric, CTA, MRA, and angiographic studies.
2. To classify Circle of Willis variations according to the affected arterial segments and morphological patterns.
3. To explain the clinical significance of these variations in collateral circulation, stroke risk, aneurysm predisposition, radiological diagnosis, and neurosurgical planning.

RESEARCH METHODOLOGY

This research was conducted to systematically identify, evaluate, and synthesize published evidence on the anatomical variations of the Circle of Willis and their clinical significance. The methodology was designed to ensure transparent study identification, selection, and synthesis of findings from human anatomical and imaging-based investigations. A structured research approach was adopted to gather evidence from multiple databases and to organize the identified variations according to their morphological characteristics and clinical implications.

2.1 Research Design

This article was conducted as a narrative literature research with a structured search strategy. Published studies addressing anatomical variations of the Circle of Willis and their clinical relevance were identified and research. Evidence from cadaveric investigations and imaging-based studies, including computed tomography angiography, magnetic resonance angiography, and digital subtraction angiography, was examined to summarize the current understanding of Circle of Willis morphology and its clinical implications.

2.2 Study Period

The literature included in this research covered studies published between January 2000 and March 2026. This period was selected to capture both classical and contemporary anatomical evidence, including more recent radiological and angiographic studies that reflect advances in imaging technology and vascular interpretation. The literature search was completed in March 2026.

2.3 Literature Search Strategy

A comprehensive electronic literature search was performed using PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. The search strategy combined keywords and related terms associated with the Circle of Willis, anatomical variation, and clinical relevance. Common search terms included “Circle of Willis,” “anatomical variations,” “cerebral arterial circle,” “hypoplasia,” “aplasia,” “fenestration,” “duplication,” “fetal-type posterior cerebral artery,” “collateral circulation,” “stroke,” “aneurysm,” and “clinical significance.” Boolean operators such as AND and OR were used to refine the search and increase retrieval relevance. Reference lists of selected articles were also screened manually to identify additional relevant studies.

2.4 Eligibility Criteria

Studies were included if they met the following criteria:

(i) investigated anatomical variations of the Circle of Willis in human subjects;
(ii) were based on cadaveric dissection, CTA, MRA, or DSA methods;
(iii) reported identifiable morphological variations or prevalence patterns;
(iv) discussed or allowed interpretation of clinical significance; and
(v) were published in English.

Studies were excluded if they:

(i) involved animal models;
(ii) were case reports with insufficient anatomical detail;
(iii) were conference abstracts, editorials, letters, or duplicate publications;
(iv) focused on unrelated cerebrovascular anatomy; or
(v) lacked sufficient methodological or anatomical information for analysis.

2.5 Study Selection Process

All records identified through database searching were imported and screened in a stepwise manner. First, duplicate articles were removed. Second, titles and abstracts were screened to exclude clearly irrelevant

studies. Third, full-text evaluation was performed for potentially eligible articles based on the predefined inclusion and exclusion criteria. Only studies meeting the eligibility criteria were included in the final research synthesis. The study selection process was documented using a PRISMA-style workflow to improve methodological clarity and reporting transparency.

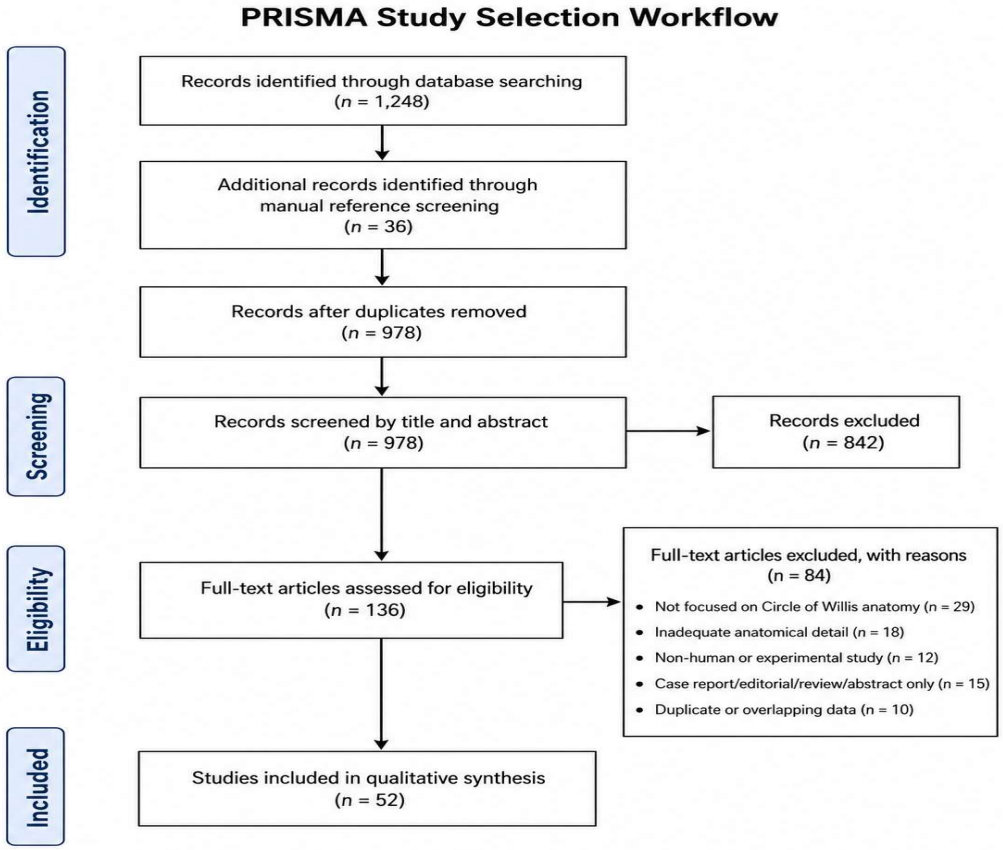

Figure 1: PRISMA-based workflow of study identification, screening, eligibility assessment, and inclusion for the research of anatomical variations of the Circle of Willis

Figure 1 illustrates the PRISMA-based workflow used for study identification and selection in this research. The process begins with the identification stage, where records are retrieved through database searching and manual reference screening. After duplicate removal, the remaining records are screened by title and abstract, and irrelevant studies are excluded. Potentially eligible articles are then assessed through full-text evaluation based on predefined inclusion and exclusion criteria. Articles excluded at this stage are reported with specific reasons, and the final eligible studies are included in the qualitative synthesis. This workflow strengthens the transparency, reproducibility, and methodological rigor of the research process.

PRISMA flow details:

Records identified through database searching (n = 1,248)

Additional records identified through other sources (n = 36)

Total records after duplicates removed (n = 978)

Records screened by title and abstract (n = 978)

Records excluded (n = 842)

Full-text articles assessed for eligibility (n = 136)

Full-text articles excluded with reasons (n = 84)

Studies included in qualitative synthesis (n = 52)

The final qualitative synthesis included 52 eligible studies. Additional references were used to support background anatomy, clinical context, imaging relevance, and discussion points, and were therefore not counted within the PRISMA-included study total.

2.6 Literature research Process

Relevant information from the selected publications was research and summarized. Particular attention was given to the types of anatomical variations reported, the arterial segments involved, the methods used for anatomical assessment, and the clinical implications discussed by the authors. Information from different studies was compared and organized thematically to facilitate synthesis and interpretation.

2.7 Thematic Synthesis of the Literature

The research studies were analyzed thematically according to the reported anatomical variation patterns. Variations were grouped into broad categories such as hypoplasia, aplasia, duplication, fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed configurations. The available literature was further examined to identify commonly discussed clinical implications related to collateral circulation, cerebrovascular disease, aneurysm formation, radiological interpretation, and neurosurgical planning. The synthesis was intended to provide an integrated overview of the current evidence regarding the anatomical and clinical significance of Circle of Willis variations.

THEMATIC SYNTHESIS OF ANATOMICAL VARIATIONS OF THE CIRCLE OF WILLIS

3.1 Normal Anatomy and Functional Importance of the Circle of Willis

The Circle of Willis is a polygonal arterial anastomotic network located at the base of the brain and serves as a major connection between the anterior and posterior cerebral circulations (Petridis & Maslehaty, 2024). In its classical configuration, it is formed by the anterior cerebral arteries, anterior communicating artery, internal carotid arteries, posterior communicating arteries, and posterior cerebral arteries (Lucifero et al., 2021). This vascular arrangement allows blood flow redistribution between the carotid and vertebrobasilar systems during arterial narrowing, occlusion, or altered cerebral perfusion (Zarrinkoob et al., 2015). Therefore, the Circle of Willis plays an important protective role in maintaining cerebral blood supply under ischemic or hemodynamic stress conditions (Lengyel et al., 2024).

A complete Circle of Willis is anatomically and clinically important because it provides effective collateral circulation when primary arterial flow is compromised (Ren et al., 2015). However, the classical complete pattern is not found in all individuals, and several studies have shown that incomplete or variant configurations are common in human populations (Liu et al., 2020; Makowicz et al., 2013). These variations may involve the anterior circulation, posterior circulation, or both, depending on the affected arterial segment (Salerno et al., 2022). The clinical effect of these variations depends not only on their morphology, but also on vessel caliber, collateral capacity, and associated cerebrovascular pathology (Deshpande et al., 2025).

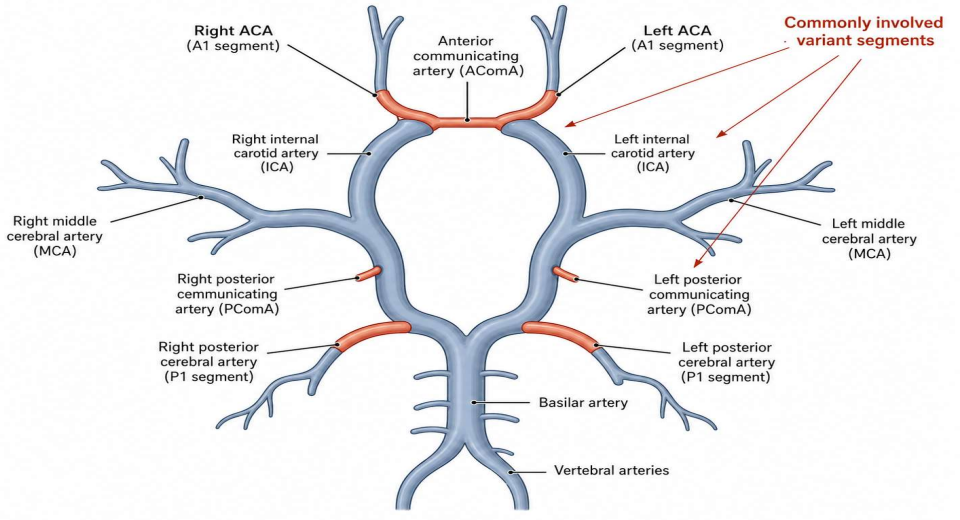

Figure 2: Vascular diagram of the normal anatomical configuration of the Circle of Willis and the commonly involved variant segments

Source: Author's own illustration based on standard anatomical descriptions and reported Circle of Willis variation patterns (Das & Al Mushaiqri, 2025; Lucifero et al., 2021; Makowicz et al., 2013; Ren et al., 2015).

Figure 2 depicts a vascular diagram of the normal Circle of Willis and highlights the arterial segments that are most frequently involved in anatomical variation. The anterior communicating artery, posterior communicating artery, A1 segment of the anterior cerebral artery, and P1 segment of the posterior cerebral artery are emphasized because these regions are commonly associated with hypoplasia, aplasia, duplication, fenestration, and fetal-type configurations. This diagram provides a clear anatomical reference for the segment-wise variations discussed in the thematic research and supports understanding of their structural and clinical relevance.

3.2 Hypoplasia of Circle of Willis Segments

Hypoplasia is one of the most frequently reported anatomical variations of the Circle of Willis and refers to underdevelopment or reduced caliber of an arterial segment (Wijesinghe et al., 2020). It commonly affects the posterior communicating artery, A1 segment of the anterior cerebral artery, and P1 segment of the posterior cerebral artery (Nas et al., 2024). A hypoplastic segment may remain anatomically present but functionally insufficient to support effective collateral circulation during ischemic events (Seifert & Heit, 2023). This makes hypoplasia clinically important because the vessel may appear continuous, yet may not provide adequate compensatory blood flow during cerebrovascular compromise (Seifert & Heit, 2023).

Hypoplasia of the A1 segment may alter blood distribution between the right and left anterior cerebral arteries and increase dependence on the contralateral A1 segment (Chen & Li, 2014). Similarly, hypoplasia of the posterior communicating artery may reduce collateral communication between the internal carotid and posterior cerebral circulation (Zhang et al., 2018). In patients with carotid stenosis or vertebrobasilar insufficiency, such hypoplastic segments may increase vulnerability to cerebral ischemia (Katsanos & Giannopoulos, 2017). Therefore, identifying hypoplastic arteries through CTA, MRA, or digital subtraction angiography is important for stroke risk assessment, collateral circulation evaluation, and treatment planning (Shaban et al., 2022).

3.3 Aplasia or Absence of Arterial Segments

Aplasia refers to the complete absence of one or more arterial segments of the Circle of Willis and may result in an incomplete arterial circle (Karatas et al., 2015). This variation is generally more clinically significant than hypoplasia because the absent segment may completely interrupt a potential collateral pathway. Absence of the anterior communicating artery, posterior communicating artery, or specific anterior or posterior cerebral arterial segments can reduce the compensatory capacity of cerebral circulation during arterial narrowing or occlusion (Karatas et al., 2015). Such incomplete configurations may limit effective blood redistribution during acute cerebrovascular compromise, especially when primary arterial flow is impaired (Foley et al., 2016).

The absence of the posterior communicating artery is particularly important because it reduces communication between the anterior and posterior cerebral circulatory systems. Incomplete posterior circulation may contribute to poor perfusion in patients with vertebrobasilar insufficiency or carotid artery disease (Dossani et al., 2022). Similarly, absence or poor development of the anterior communicating artery may affect cross-flow between the right and left anterior cerebral arteries, especially in steno-occlusive carotid artery disease (Schulte-Altedorneburg & Becker, 2005). For this reason, aplastic segments are highly relevant in CTA, MRA, angiographic evaluation, cerebrovascular surgery, and preoperative vascular mapping (Laviv et al., 2017).

3.4 Duplication, Fenestration, and Accessory Vessels

Duplication and fenestration are less common but clinically relevant structural variations of the Circle of Willis. Duplication occurs when an arterial segment appears as two parallel vascular channels, whereas fenestration refers to the division of a single arterial segment into two channels that subsequently rejoin (Chng et al., 2004; Vasović et al., 2002). These variations are commonly reported in the anterior communicating artery and vertebrobasilar region, although they may also occur in other components of the cerebral arterial circle (Songur et al., 2008). Their occurrence is generally associated with developmental variation during embryological vascular remodeling (Curtis et al., 2012).

Fenestrated and duplicated vessels may have clinical relevance because altered vessel configuration can influence local blood flow patterns and increase hemodynamic stress at arterial junctions (Saha et al., 2024). Such altered stress may contribute to aneurysm formation, particularly at arterial bifurcations or communicating artery regions. Accessory vessels, additional communicating channels, or unusual arterial branches may also complicate radiological interpretation and surgical exposure (Kaufman & Lee, 2013; Ojha et al., 2023). Therefore, these variations should be carefully identified and documented during neurovascular imaging, angiographic evaluation, and operative planning.

3.5 Fetal-Type Posterior Cerebral Artery

Fetal-type posterior cerebral artery is a clinically important variation in which the posterior cerebral artery receives dominant blood supply from the internal carotid artery through the posterior communicating artery rather than from the basilar artery (Tan & Roberts, 2021). This variation may be complete or partial depending on the caliber of the P1 segment and the degree of contribution from the basilar circulation (Lapraz et al., 2023). In a

complete fetal-type configuration, the P1 segment may be absent or severely hypoplastic, making the posterior cerebral territory highly dependent on carotid circulation (Davidoiu et al., 2023). This arrangement changes the normal balance between anterior and posterior cerebral blood supply (Vasović et al., 2008).

The fetal-type posterior cerebral artery has important implications for stroke mechanisms and vascular intervention (Ryu & Kim, 2022). In patients with internal carotid artery stenosis or occlusion, a fetal-type posterior cerebral artery may increase the risk of ischemia in the posterior cerebral artery territory (Davidoiu et al., 2023). It may also influence aneurysm formation near the posterior communicating artery due to altered flow direction and increased hemodynamic load (Baek et al., 2009). Thus, fetal-type posterior cerebral artery should be considered a clinically meaningful variation rather than a minor anatomical finding, particularly in cerebrovascular imaging, stroke evaluation, and surgical planning (Lambert et al., 2016).

3.6 Population-Based and Imaging-Based Variation Patterns

Reported frequencies of Circle of Willis variations differ across populations and study methods (Eftekhar et al., 2006). Cadaveric studies provide direct anatomical visualization of arterial segments, although they may be limited by sample size, age distribution, and postmortem vascular changes. CTA and MRA studies allow non-invasive evaluation of vascular anatomy in living subjects and are useful for identifying clinically relevant arterial configurations. Digital subtraction angiography provides high-resolution vascular detail, but it is usually performed in selected clinical populations, which may affect the generalizability of findings.

Variation patterns may also differ according to age, sex, ethnicity, vascular risk factors, and the presence of cerebrovascular disease. Some studies report higher rates of incomplete posterior circulation, while others identify anterior communicating artery and A1 segment variations as frequent findings (Salerno et al., 2022). These differences suggest that Circle of Willis morphology should be interpreted in relation to both anatomical background and clinical context (Jones et al., 2021). Therefore, combined analysis of cadaveric and imaging-based studies provides a more comprehensive understanding of normal and variant cerebral arterial anatomy.

3.7 Clinical Significance of Circle of Willis Variations

The clinical significance of Circle of Willis variations is mainly related to their effects on collateral circulation, stroke risk, aneurysm formation, and surgical planning. A complete and functionally competent Circle of Willis can support cerebral perfusion by redirecting blood flow through alternate arterial pathways during vascular compromise. In contrast, incomplete, hypoplastic, or aplastic configurations may impair collateral compensation and increase the risk of ischemic damage during arterial occlusion (Desikan et al., 2024). This is particularly important in patients with carotid artery stenosis, vertebrobasilar insufficiency, or acute ischemic stroke (Vilela & Goulao, 2005).

Circle of Willis variations may also influence aneurysm development because abnormal vessel geometry can produce uneven hemodynamic stress at arterial junctions (Shen et al., 2022). The anterior communicating artery and posterior communicating artery are clinically important sites because they are frequently associated with variant anatomy and aneurysm formation (Kardile et al., 2013). For radiologists, accurate recognition of these variations improves CTA, MRA, and angiographic interpretation (Zampakis et al., 2015). For neurosurgeons and interventional neuroradiologists, preoperative identification of vascular variants helps reduce procedural risk during aneurysm clipping, coiling, bypass surgery, and skull-base approaches (Wei et al., 2022).

3.8 Summary of Thematic Findings

The thematic synthesis shows that the Circle of Willis presents wide anatomical variability involving both anterior and posterior circulatory components (Jones et al., 2021). Hypoplasia, aplasia, duplication, fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed configurations represent the major variation patterns reported in the literature (Kowalewska et al., 2025). Among these, hypoplasia and aplasia of communicating arteries and fetal-type posterior cerebral artery appear to have the strongest clinical relevance because of their effect on collateral circulation and cerebrovascular risk (Davidoiu et al., 2023; Jones et al., 2021). Overall, the evidence supports the need for a segment-based morpho-clinical interpretation of Circle of Willis variations to improve anatomical classification, radiological diagnosis, and clinical decision-making (Han et al., 2011).

RESULTS AND THEMATIC FINDINGS

4.1 Overview of Included Studies

The research studies showed that anatomical variations of the Circle of Willis are consistently reported across cadaveric, computed tomography angiography, magnetic resonance angiography, and digital subtraction angiography-based investigations (Han et al., 2011; Karatas et al., 2015; Jones et al., 2021; Wijesinghe et al., 2020). The included evidence indicated that the classical complete and symmetrical Circle of Willis is less frequent than the textbook description, while incomplete, hypoplastic, aplastic, duplicated, fenestrated, and fetal-type configurations are commonly observed (Davidoiu et

al., 2023; Eftekhar et al., 2006; Vasović et al., 2002). Across the research literature, posterior circulation variations were frequently reported, particularly involving the posterior communicating artery and P1 segment, while anterior circulation variations commonly involved the anterior communicating artery and A1 segment (Chen & Li, 2014; Kardile et al., 2013; Nas et al., 2024; Zampakis et al., 2015). These findings confirm that Circle of Willis morphology should be interpreted as a variable anatomical system with direct implications for collateral circulation, cerebrovascular disease, radiological diagnosis, and neurosurgical planning (Desikan et al., 2024; Lengyel et al., 2024; Shen et al., 2022; Zampakis et al.,2015).

Table 1: Summary of included studies on Circle of Willis anatomical variations

Evidence category	Main method	Main anatomical focus	Dominant findings	Clinical relevance	Supporting references
Cadaveric studies	Gross anatomical dissection	Direct visualization of arterial segments	Hypoplasia, aplasia, duplication, and incomplete arterial circles	Useful for anatomical education and surgical orientation	Eftekhar et al. (2006); Vasović et al. (2002); Wijesinghe et al. (2020)
CTA-based studies	Computed tomography angiography	Living vascular morphology and vessel caliber	High detection of segmental hypoplasia and incomplete posterior circulation	Useful for stroke risk assessment and preoperative planning	Han et al. (2011); Karatas et al. (2015); Zampakis et al. (2015)
MRA-based studies	Magnetic resonance angiography	Non-invasive assessment of cerebral arterial patterns	Frequent variation in PComA, A1, and P1 segments	Useful for screening and cerebrovascular evaluation	Chen and Li (2014); Nas et al. (2024); Zarrinkoob et al. (2015)
DSA-based studies	Digital subtraction angiography	Detailed arterial lumen and flow-related anatomy	Clear identification of aneurysm-related and flow-related variants	Useful for endovascular intervention planning	Han et al. (2011); Shaban et al. (2022); Wei et al. (2022)
Mixed-method studies	Cadaveric and imaging-based comparison	Combined anatomical and clinical interpretation	Variation frequency differs by method, population, and diagnostic criteria	Supports integrated morpho-clinical interpretation	Jones et al. (2021); Liu et al. (2020); Salerno et al. (2022)

Source: Author's synthesis based on the research literature

4.2 Classification of Circle of Willis Variations

The anatomical variations of the Circle of Willis identified in the research literature can be classified into six major morphological categories: hypoplasia, aplasia or absence, duplication and fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed-pattern configurations (Davidoiu et al., 2023; Jones et al., 2021; Vasović et al., 2002). This classification is useful because it separates vessel narrowing, vessel absence, structural duplication, developmental persistence, and combined variation patterns into clinically understandable groups (Liu et al., 2020; Nas et al., 2024). Such grouping also supports a segment-based interpretation of the Circle of Willis, where each variation is linked to the affected artery and its possible clinical consequence (Han et al., 2011; Zampakis et al., 2015).

4.2.1 Hypoplasia

Hypoplasia refers to reduced development or narrowing of an arterial segment while the vessel remains anatomically present (Wijesinghe et al., 2020). It is one of the most frequently reported variations of the Circle of Willis and commonly affects the posterior communicating artery, A1 segment, and P1 segment (Chen & Li, 2014; Nas et al., 2024). Although a hypoplastic vessel may appear continuous on imaging, its reduced diameter may limit effective collateral flow during arterial stenosis or occlusion (Seifert & Heit, 2023). Therefore, hypoplasia has important clinical relevance in patients with carotid artery disease, vertebrobasilar insufficiency, and ischemic stroke risk (Katsanos & Giannopoulos, 2017; Shaban et al., 2022).

4.2.2 Aplasia or Absence

Aplasia refers to the complete absence of an arterial segment within the Circle of Willis (Karatas et al., 2015). Compared with hypoplasia, aplasia may have greater clinical significance because it can completely interrupt collateral communication between arterial territories. Absence of the anterior communicating artery can reduce cross-flow between the two anterior cerebral arteries, while absence of the posterior communicating artery can weaken communication between the anterior and posterior circulations (Dossani et al., 2022; Schulte-Altedorneburg & Becker, 2005). Such incomplete configurations may increase vulnerability to ischemia when primary cerebral blood supply is compromised (Foley et al., 2016; Vilela & Goulao, 2005).

4.2.3 Duplication and Fenestration

Duplication and fenestration are developmental variations in which an arterial segment divides into two channels or appears as paired vascular channels (Chng et al., 2004; Vasović et al., 2002). Fenestration occurs when a single vessel divides into two parallel channels that later rejoin, while duplication refers to the presence of two separate arterial channels along a segment (Chng et al., 2004). These variations are often reported in the anterior communicating artery and vertebrobasilar regions and may be associated with altered local hemodynamics (Songur et al., 2008). Because hemodynamic stress is an important factor in aneurysm formation, duplicated or fenestrated segments require careful evaluation during CTA, MRA, or angiographic assessment (Baek et al., 2009; Shen et al., 2022).

4.2.4 Accessory Vessels

Accessory vessels represent additional arterial branches or communicating channels beyond the usual configuration of the Circle of Willis (Kowalewska et al., 2025). These vessels may occur as accessory anterior cerebral arteries, additional communicating branches, or unusual arterial connections. Although some accessory vessels may provide supplementary circulation, they can also complicate radiological interpretation and surgical exposure (Kaufman & Lee, 2013; Ojha et al., 2023). Their recognition is important during preoperative vascular mapping, aneurysm surgery, and endovascular procedures (Shaban et al., 2022; Zampakis et al., 2015).

4.2.5 Fetal-Type Posterior Cerebral Artery

Fetal-type posterior cerebral artery is a major developmental variation in which the posterior cerebral artery receives dominant blood supply from the internal carotid artery through the posterior communicating artery rather than from the basilar artery (Tan & Roberts, 2021). In complete fetal-type configuration, the P1 segment may be absent or markedly hypoplastic, whereas in partial fetal-type configuration, both carotid and basilar contributions may be present (Davidoiu et al., 2023; Lapraz et al., 2023). This variation changes the normal balance of anterior and posterior cerebral circulation and may increase dependence of the posterior cerebral territory on the internal carotid artery (Vasović et al., 2008). It is clinically relevant in carotid stenosis, posterior circulation ischemia, aneurysm evaluation, and endovascular planning (Lambert et al., 2016; Ryu & Kim, 2022).

4.2.6 Mixed-Pattern Configurations

Mixed-pattern configurations occur when two or more variations are present in the same Circle of Willis. Examples include combined A1 hypoplasia with posterior communicating artery aplasia, fetal-type posterior cerebral artery with P1 hypoplasia, or fenestration associated with accessory vessels (Kowalewska et al., 2025). These patterns are clinically important because the combined effect of multiple variations may produce greater impairment of collateral circulation than a single isolated variation (Jones et al., 2021; Liu et al., 2020). Therefore, mixed configurations should be evaluated as integrated vascular patterns rather than separate anatomical findings, particularly in radiological diagnosis and neurosurgical planning (Han et al., 2011; Zampakis et al., 2015).

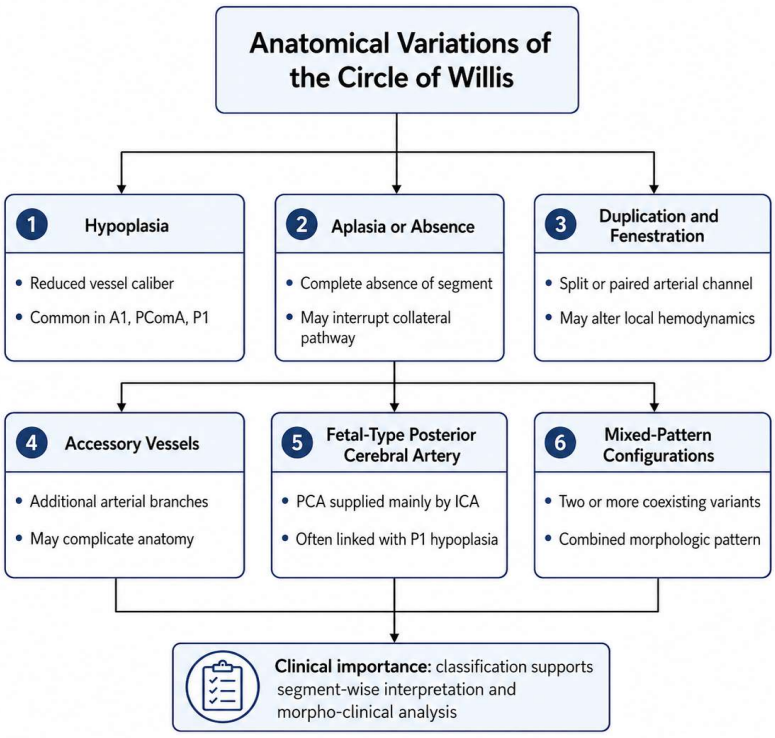

Figure 3: Classification diagram of anatomical variations of the Circle of Willis
Source: Author's own classification based on reported Circle of Willis variation patterns in the research literature (Davidoiu et al., 2023; Jones et al., 2021; Liu et al., 2020; Nas et al., 2024; Vasović et al., 2002)

Figure 3 summarizes the major categories of Circle of Willis variation, including hypoplasia, aplasia, duplication, fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed-pattern configurations. The figure presents these variation groups in a clear classification format so that readers can understand how different morphological patterns are organized for thematic interpretation. This classification provides the foundation for the segment-wise and morpho-clinical analysis presented in the following sections.

4.3 Segment-Wise Distribution of Variations

The research literature showed that Circle of Willis variations are not uniformly distributed across all arterial segments. The anterior communicating artery, A1 segment, posterior communicating artery, and P1 segment have been repeatedly identified as commonly involved variant regions (Chen & Li, 2014; Jones et al., 2021; Kardile et al., 2013; Nas et al., 2024). Segment-wise analysis is important because the clinical consequence of a variation depends strongly on which arterial connection is affected (Han et al., 2011; Zampakis et al., 2015). For example, variation in the anterior communicating artery may affect interhemispheric collateral flow, whereas variation in the posterior communicating artery or P1 segment may affect communication between the carotid and vertebrobasilar systems (Davidoiu et al., 2023; Schulte-Altedorneburg & Becker, 2005).

4.3.1 Anterior Communicating Artery Variations

The anterior communicating artery is one of the most variable and clinically important components of the Circle of Willis (Kardile et al., 2013). Reported variations include hypoplasia, aplasia, duplication, fenestration, and complex branching patterns (Makowicz et al., 2013; Vasović et al., 2002). Because this artery connects the right and left anterior cerebral arteries, its absence or underdevelopment may reduce cross-flow between the two hemispheres (Schulte-Altedorneburg & Becker, 2005). It is also a common site for aneurysm formation because of its small caliber, branching complexity, and exposure to hemodynamic stress (Kardile et al., 2013; Shen et al., 2022).

4.3.2 A1 Segment Variations

The A1 segment of the anterior cerebral artery plays an important role in supplying the anterior cerebral circulation and supporting collateral flow through the anterior communicating artery (Lucifero et al., 2021). A1 hypoplasia or aplasia may shift blood flow dependence toward the contralateral A1 segment (Chen & Li, 2014).

This asymmetry may increase hemodynamic load on the opposite side and may contribute to aneurysm development near the anterior communicating artery complex (Chen & Li, 2014; Shen et al., 2022). In ischemic conditions, A1 variation may also reduce compensatory flow to the affected hemisphere (Seifert & Heit, 2023).

4.3.3 Posterior Communicating Artery Variations

The posterior communicating artery connects the internal carotid artery with the posterior cerebral circulation and is essential for anterior–posterior collateral communication (Tan & Roberts, 2021). Hypoplasia or absence of the posterior communicating artery may reduce the ability of the Circle of Willis to compensate during carotid or vertebrobasilar insufficiency (Jones et al., 2021; Lengyel et al., 2024). Conversely, a large posterior communicating artery may be associated with fetal-type posterior cerebral artery configuration (Davidoiu et al., 2023). These variations are clinically important in stroke evaluation, aneurysm assessment, and endovascular intervention (Ryu & Kim, 2022; Zampakis et al., 2015).

4.3.4 P1 Segment Variations

The P1 segment of the posterior cerebral artery connects the basilar artery to the posterior cerebral circulation and contributes to the posterior part of the Circle of Willis (Tan & Roberts, 2021). Hypoplasia or absence of the P1 segment is often associated with fetal-type posterior cerebral artery (Davidoiu et al., 2023; Nas et al., 2024). When the P1 segment is underdeveloped, the posterior cerebral territory may become more dependent on blood flow from the internal carotid artery through the posterior communicating artery (Lambert et al., 2016). This configuration may affect ischemic patterns and influence interpretation of posterior circulation symptoms (Ryu & Kim, 2022; Salerno et al., 2022).

4.3.5 Other Less Frequent Segmental Variations

Less frequent variations may involve the internal carotid artery bifurcation, middle cerebral artery origin, distal anterior cerebral artery, basilar apex, or accessory communicating channels (Kowalewska et al., 2025; Makowicz et al., 2013). Although these variations are less commonly reported than AComA, A1, PComA, and P1 variations, they remain clinically important during imaging interpretation and surgical planning (Han et al., 2011; Zampakis et al., 2015). Their significance increases when they coexist with other Circle of Willis abnormalities or cerebrovascular disease (Deshpande et al., 2025; Jones et al., 2021). Therefore, complete vascular assessment should include both common and uncommon segmental variants.

4.4 Anatomical Variations and Their Reported Clinical Implications

Morpho-clinical mapping links each anatomical variation with its possible functional and clinical implication. This approach is useful because the same morphological variation may have different clinical effects depending on the affected arterial segment, vessel caliber, collateral demand, and associated vascular disease (Deshpande et al., 2025; Liu et al., 2020). For example, A1 hypoplasia mainly affects anterior cross-flow, whereas posterior communicating artery hypoplasia affects anterior–posterior collateral communication (Chen & Li, 2014; Jones et al., 2021). Similarly, fetal-type posterior cerebral artery changes posterior cerebral perfusion dependence from the basilar system to the carotid system (Davidoiu et al., 2023; Lambert et al., 2016).

Table 2: Segment-wise classification and clinical significance of Circle of Willis variations

Variation type	Commonly affected segment	Morphological meaning	Possible clinical significance	Diagnostic/surgical relevance	Supporting references
Hypoplasia	A1, PComA, P1	Reduced vessel caliber	Reduced collateral flow and increased ischemic vulnerability	Important in CTA/MRA stroke evaluation	Chen and Li (2014); Nas et al. (2024); Wijesinghe et al. (2020)
Aplasia or absence	AComA, PComA, P1	Complete absence of vessel segment	Interrupted collateral pathway	Important in preoperative vascular mapping	Karatas et al. (2015); Schulte-Altedorneburg and

Variation type	Commonly affected segment	Morphological meaning	Possible clinical significance	Diagnostic/surgical relevance	Supporting references
					Becker (2005)
Duplication	AComA, ACA region	Presence of two parallel arterial channels	May alter local flow pattern	Important during aneurysm surgery	Chng et al. (2004); Vasović et al. (2002)
Fenestration	AComA, basilar region	Split vessel segment that rejoins	Possible hemodynamic stress and aneurysm association	Important in angiographic interpretation	Chng et al. (2004); Songur et al. (2008); Shen et al. (2022)
Accessory vessels	ACA/PComA region	Additional arterial branch or channel	May provide supplementary flow or complicate anatomy	Important in surgical exposure and radiology	Kowalewska et al. (2025); Zampakis et al. (2015)
Fetal-type PCA	PComA and P1	PCA supplied mainly by ICA	Posterior cerebral territory becomes carotid-dependent	Important in carotid stenosis and posterior ischemia	Davidoiu et al. (2023); Lambert et al. (2016); Ryu and Kim (2022)
Mixed configuration	Multiple segments	Combination of two or more variations	Greater potential reduction in collateral efficiency	Important in complex vascular planning	Jones et al. (2021); Kowalewska et al. (2025); Liu et al. (2020)

Source: Author's synthesis based on the research literature

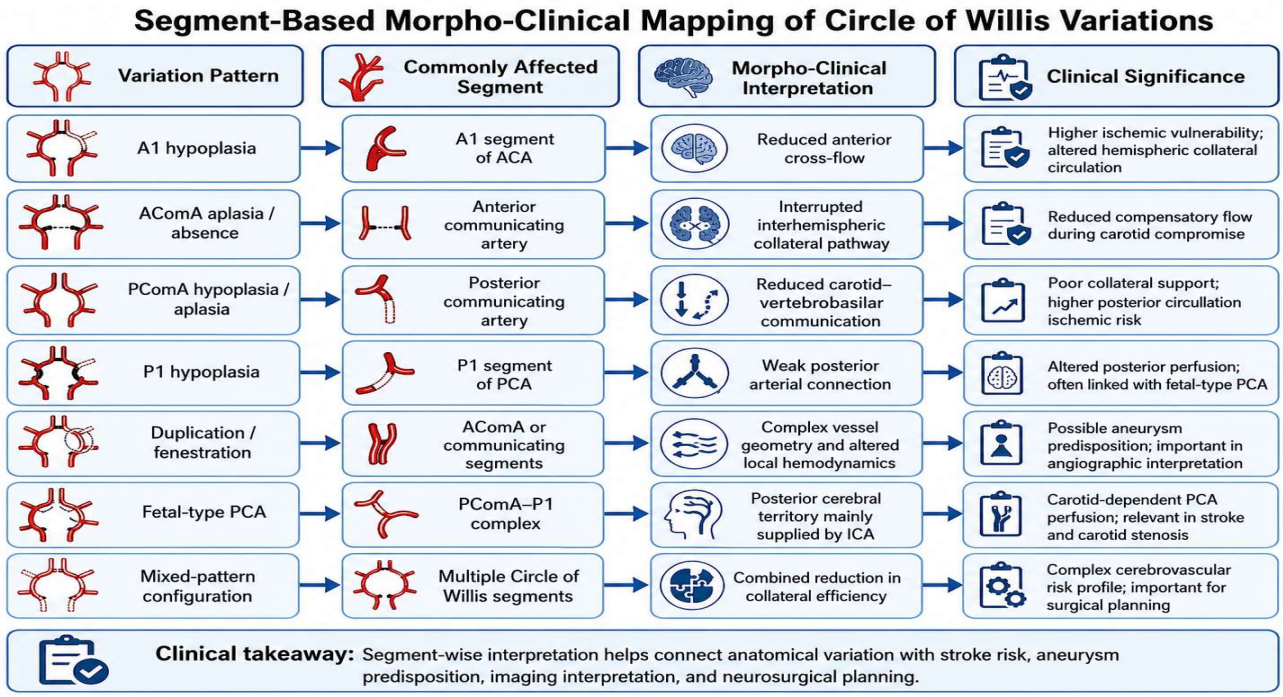

Figure 4: Summary of Reported Anatomical Variations of the Circle of Willis and Their Clinical Implications
Source: Author's own synthesis based on reported anatomical variation patterns and clinical implications in the research literature (Chen & Li, 2014; Davidoiu et al., 2023; Jones et al., 2021; Shen et al., 2022; Zampakis et al., 2015).

Figure 4 summarizes information reported in the research literature by illustrating the relationship between common anatomical variations of the Circle of Willis and their potential clinical implications. The figure provides a simplified visual overview of findings frequently discussed in anatomical, radiological, and clinical studies. Figure 4 visually connects variation type, affected arterial segment, and clinical relevance. For example, A1 hypoplasia may be linked with reduced anterior collateral flow and stroke vulnerability; posterior communicating artery hypoplasia may be linked with reduced carotid–basilar collateral communication; anterior communicating artery fenestration may be linked with altered hemodynamic stress and aneurysm predisposition; and fetal-type posterior cerebral artery may be linked with carotid-dependent posterior cerebral perfusion. This figure represents the main novelty of the research because it translates anatomical variation into clinically meaningful interpretation.

4.5 Clinical Relevance of Major Variation Patterns

The clinical relevance of Circle of Willis variations is mainly related to collateral circulation efficiency, stroke risk, aneurysm predisposition, radiological interpretation, and neurosurgical or endovascular planning (Desikan et al., 2024; Jones et al., 2021; Shen et al., 2022; Zampakis et al., 2015). A complete and functionally competent Circle of Willis can support alternative routes of blood flow during arterial narrowing or occlusion (He et al., 2026; Kubicki et al., 2026; Lengyel et al., 2024). In contrast, incomplete or hypoplastic configurations may reduce compensatory capacity and increase clinical vulnerability during cerebrovascular events (Gaigalaite et al., 2026; Seifert & Heit, 2023). Therefore, anatomical variation should be considered an important factor in both diagnostic and therapeutic decision-making (Han et al., 2011; Shaban et al., 2022).

4.5.1 Collateral Circulation Efficiency

Collateral circulation is the most important functional role of the Circle of Willis because it allows redistribution of blood flow when a primary arterial pathway is compromised (He et al., 2026; Ren et al., 2015). A complete arterial circle can support cerebral perfusion through communicating arteries during carotid stenosis, vertebrobasilar insufficiency, or acute arterial occlusion (Kubicki et al., 2026; Lengyel et al., 2024). However, hypoplasia or absence of the anterior communicating artery, posterior communicating artery, A1 segment, or P1 segment may reduce this compensatory mechanism (Chen & Li, 2014; Jones et al., 2021; Nas et al., 2024). This explains why individuals with similar degrees of arterial stenosis may show different clinical outcomes depending on Circle of Willis completeness, vessel caliber, and collateral capacity (Desikan et al., 2024; Zarrinkoob et al., 2015).

4.5.2 Stroke and Ischemic Risk

Incomplete Circle of Willis configurations may increase susceptibility to ischemic stroke by limiting collateral blood flow during arterial occlusion (Gaigalaite et al., 2026; Seifert & Heit, 2023). Posterior communicating artery hypoplasia or aplasia may reduce anterior–posterior collateral communication, while A1 or anterior communicating artery variation may reduce cross-flow between the two hemispheres (Chen & Li, 2014; Jones et al., 2021; Schulte-Altedorneburg & Becker, 2005). Fetal-type posterior cerebral artery may also influence ischemic patterns because the posterior cerebral territory becomes dependent on carotid circulation (Davidoiu et al., 2023; Lambert et al., 2016; Ryu & Kim, 2022). Therefore, Circle of Willis morphology is clinically relevant in stroke risk assessment, acute cerebrovascular evaluation, and interpretation of ischemic patterns (Salerno et al., 2022; Vilela & Goulao, 2005).

4.5.3 Aneurysm Predisposition

Aneurysm formation is influenced by vessel wall structure, branching anatomy, and hemodynamic stress (Baek et al., 2009; Shen et al., 2022). Variations such as A1 asymmetry, anterior communicating artery duplication, fenestration, and fetal-type posterior cerebral artery may alter local blood flow and increase stress at arterial junctions (Chen & Li, 2014; Kardile et al., 2013; Lapraz et al., 2023). The anterior communicating artery and posterior communicating artery are especially important because they are common sites of both anatomical variation and aneurysm formation (Kardile et al., 2013; Zeng et al., 2026). Thus, careful evaluation of Circle of Willis anatomy is essential in aneurysm diagnosis, rupture-risk interpretation, and treatment planning (Shen et al., 2022; Wei et al., 2022).

4.5.4 Radiological Interpretation

Accurate identification of Circle of Willis variations is essential during CTA, MRA, and DSA interpretation (Han et al., 2011; Karatas et al., 2015; Zampakis et al., 2015). Hypoplastic vessels may be mistaken for absent vessels if imaging resolution is limited, while fenestration or duplication may be misinterpreted as vascular pathology (Chng et al., 2004; Vasović et al., 2002). Fetal-type posterior cerebral artery should be recognized because it changes the expected source of posterior cerebral artery perfusion (Davidoiu et al., 2023; Lambert et al., 2016). Radiologists should therefore report clinically relevant Circle of Willis variations, especially in patients being evaluated for stroke, aneurysm, carotid stenosis, or neurosurgical intervention (Shaban et al., 2022; Zampakis et al., 2015).

4.5.5 Neurosurgical and Endovascular Planning

Knowledge of Circle of Willis variation is important for neurosurgical and endovascular procedures because variant arteries may alter surgical corridors, increase the risk of vascular injury, or affect procedural feasibility (Dowlati et al., 2026; Zeng et al., 2026). Variations involving the anterior communicating artery, posterior communicating artery, A1 segment, and P1 segment are particularly important during aneurysm clipping, endovascular coiling, bypass surgery, and skull-base approaches (Kardile et al., 2013; Zampakis et al., 2015). Preoperative identification of hypoplastic, aplastic, duplicated, fenestrated, or accessory vessels helps reduce procedural complications and improves surgical planning (Han et al., 2011; Shaban et al., 2022). Therefore, segment-wise vascular mapping should be considered a practical requirement before complex cerebrovascular intervention (Wei et al., 2022; Zeng et al., 2026).

4.6 Summary of Key Thematic Findings

The thematic findings show that anatomical variation is a normal and clinically meaningful feature of the Circle of Willis rather than an incidental abnormality (Jones et al., 2021). The most important variation patterns include hypoplasia, aplasia, duplication, fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed configurations (Davidoiu et al., 2023; Kowalewska et al., 2025; Vasović et al., 2002). Among these, variations involving the anterior communicating artery, posterior communicating artery, A1 segment, and P1 segment have the greatest clinical importance because they directly influence collateral circulation, stroke vulnerability, aneurysm predisposition, imaging interpretation, and surgical planning (Chen & Li, 2014; Jones et al., 2021; Nas et al., 2024; Zampakis et al., 2015). Overall, the results support the use of a segment-based morpho-clinical approach for interpreting Circle of Willis variations in anatomy, radiology, neurology, and neurosurgery.

4.7 Discussion

The literature research in this article demonstrates that anatomical variation of the Circle of Willis is a common feature of human cerebral vascular anatomy. Published studies consistently report that the classical complete configuration is less frequent than traditionally described in anatomical textbooks. Variations such as hypoplasia, aplasia, duplication, fenestration, accessory vessels, and fetal-type posterior cerebral artery have been documented across diverse populations using both cadaveric and imaging-based methods. The research evidence suggests that these variations may influence collateral circulation, cerebrovascular risk, radiological interpretation, and neurosurgical planning.

4.8 Limitations

1.This research is based on previously published cadaveric, CTA, MRA, and angiographic studies; therefore, variation frequencies may differ according to

study design, population characteristics, imaging method, and diagnostic criteria.

2.A quantitative meta-analysis was not performed because the included studies used different definitions for hypoplasia, aplasia, completeness, and fetal-type posterior cerebral artery.

3.Clinical associations such as stroke risk, aneurysm predisposition, and collateral circulation efficiency were interpreted from available literature, but direct patient-level outcome validation was limited.

CONCLUSION

This research confirms that anatomical variations of the Circle of Willis are common and clinically significant vascular patterns that influence cerebral collateral circulation, ischemic vulnerability, aneurysm predisposition, radiological interpretation, and neurosurgical planning. Variations such as hypoplasia, aplasia, duplication, fenestration, accessory vessels, fetal-type posterior cerebral artery, and mixed configurations should not be considered incidental anatomical findings, as their effects depend on the involved arterial segment and functional collateral capacity. The segment-based morpho-clinical mapping approach used in this research provides a practical framework for linking anatomical variation with clinical relevance, thereby supporting improved interpretation in anatomy, radiology, neurology, and cerebrovascular surgery.

Future work: Future multicenter imaging and cadaveric studies should use standardized definitions and patient-level clinical correlation to validate the prognostic significance of Circle of Willis variations.

REFERENCES

1. Baek, H., Jayaraman, M. V., & Karniadakis, G. E. (2009). Wall shear stress and pressure distribution on aneurysms and infundibulae in the posterior communicating artery bifurcation. Annals of Biomedical Engineering, 37(12), 2469–2487.
2. Beneš, V., Bubeníková, A., & Netuka, D. (2026). History of cerebral ischemia treatment: "A generation which ignores history has no past and no future." In Surgical and Interventional Treatment of Cerebral Ischemia: Basic Science to Clinical Practice (pp. 1–10). Springer Nature Switzerland.
3. Cai, Y., Li, J., Chen, Y., Ou, Z., Wei, J., Long, X., ... & Zeng, J. (2026). G6PD deficiency is implicated in Circle of Willis variants in stroke patients and impairs brain vasculature in zebrafish. Journal of Cerebral Blood Flow & Metabolism, 46(3), 738–752.
4. Chen, H., & Li, M. H. (2014). A1 segment hypoplasia accompanied by AcomA aneurysms assessed with magnetic resonance angiography. Surgical and Radiologic Anatomy, 36(4), 353–357.
5. Chng, S. M., Alvarez, H., Marsot-Dupuch, K., Mercier, P., & Lasjaunias, P. (2004). "Duplicated" or "multiple" cervical internal carotid and vertebral arteries from fenestration, duplication and vasa vasorum to segmental rete. Interventional Neuroradiology, 10(4), 301–307.
6. Curtis, C. D., Davis, R. B., Ingram, K. G., & Griffin, C. T. (2012). Chromatin-remodeling complex specificity and embryonic vascular development. Cellular and Molecular Life Sciences, 69(23), 3921–3931.
7. Das, S., & Al Mushaiqri, M. (2025). Anatomy of the blood vessels supplying the brain and its clinical importance in neurovisualization. In Visualization in Neuroanatomical Sciences (pp. 173–188). Springer Nature Switzerland.
8. Davidoiu, A. M., Mincă, D. I., Rusu, M. C., Hostiuc, S., & Toader, C. (2023). The fetal type of posterior cerebral artery. Medicina, 59(2), 231.
9. de Liyis, B. G., Nathania, N., Hartono, O., Alhaq, A. M. G., Sihombing, E. J. N., Hafif, M., ... & July, J. (2026). Shifting the paradigm in intracranial aneurysm detection with deep learning: A diagnostic accuracy meta-analysis and meta-regression. Neurosurgical Review, 49(1), 259.
10. de Sousa, Í. A., Machado, A. D. S., Veras, A. D. O., Goulart, T. O., Tatsuta, S. G., Gonçalves, T. A. P., ... & Pontes-Neto, O. M. (2026). Reversible cerebral vasoconstriction syndrome: A narrative review. Headache: The Journal of Head and Face Pain.
11. Deshpande, A., Zhang, L. Q., Balu, R., Yahyavi-Firouz-Abadi, N., Badjatia, N., Laksari, K., & Tahsili-Fahadan, P. (2025). Cerebrovascular morphology: Insights into normal variations, aging effects and disease implications. Journal of Cerebral Blood Flow & Metabolism, 45(7), 1249–1264.
12. Desikan, S. K., Brahmbhatt, B., Patel, J., Kankaria, A. A., Anagnostakos, J., Dux, M., ... & Lal, B. K. (2024). Cognitive impairment in asymptomatic carotid artery stenosis is associated with abnormal segments in the Circle of Willis. Journal of Vascular Surgery, 80(3), 746–755.
13. Dossani, R. H., Cappuzzo, J. M., Waqas, M., Almeida, N., & Levy, E. I. (2022). Posterior circulation stroke and vertebrobasilar insufficiency. In Introduction to Vascular Neurosurgery (pp. 311–330). Springer International Publishing.
14. Dowlati, E., Harake, E. S., Koduri, S., Pandey, A., & Mergos, J. (2026). Endovascular embolization of cerebral aneurysms and arteriovenous malformations. In Operative Neurophysiology: Practical Application for Comprehensive Neuromonitoring and Neuromapping Techniques (pp. 709–744). Springer Nature Switzerland.

15. Eftekhar, B., Dadmehr, M., Ansari, S., Ghodsi, M., Nazparvar, B., & Ketabchi, E. (2006). Are the distributions of variations of Circle of Willis different in different populations? Results of an anatomical study and review of literature. BMC Neurology, 6(1), 22.

16. Foley, L. S., Yamanaka, K., & Reece, T. B. (2016). Arterial cannulation and cerebral perfusion strategies for aortic arch operations. Seminars in Cardiothoracic and Vascular Anesthesia, 20(4), 298–302.

17. Gaigalaite, V., Vilimas, A., Dementaviciene, J., Varvuolyte, S., & Slautaite, I. (2026). Interaction between vertebral artery hypoplasia and Circle of Willis variants in posterior circulation stroke and TIA. Frontiers in Neurology, 17, 1752669.

18. Han, A., Yoon, D. Y., Chang, S. K., Lim, K. J., Cho, B. M., Shin, Y. C., ... & Kim, K. H. (2011). Accuracy of CT angiography in the assessment of the Circle of Willis: Comparison of volume-rendered images and digital subtraction angiography. Acta Radiologica, 52(8), 889–893.

19. He, G., Feng, H., Li, S., An, H., Jiang, B., Ouyang, L., ... & Chen, Y. (2026). Collateral circulation outweighs therapeutic modality in predicting outcomes of symptomatic MCA stenosis: A triple-center retrospective cohort. World Neurosurgery, 124915.

20. Jones, J. D., Castanho, P., Bazira, P., & Sanders, K. (2021). Anatomical variations of the Circle of Willis and their prevalence, with a focus on the posterior communicating artery: A literature review and meta-analysis. Clinical Anatomy, 34(7), 978–990.

21. Karatas, A., Coban, G., Cinar, C., Oran, I., & Uz, A. (2015). Assessment of the Circle of Willis with cranial tomography angiography. Medical Science Monitor, 21, 2647.

22. Kardile, P. B., Ughade, J. M., Pandit, S. V., & Ughade, M. N. (2013). Anatomical variations of anterior communicating artery. Journal of Clinical and Diagnostic Research, 7(12), 2661.

23. Katsanos, A. H., & Giannopoulos, S. (2017). Increased risk for posterior circulation ischaemia in patients with vertebral artery hypoplasia: A systematic review and meta-analysis. European Stroke Journal, 2(2), 171–177.

24. Kaufman, J. A., & Lee, M. J. (2013). Vascular and interventional radiology: The requisites. Elsevier Health Sciences.

25. Khayat, O. G., Bentamra, L., Houari, I., Belfkih, R., Smadja, D., & Chausson, N. (2026). Neurosonology in acute stroke revealing bilateral internal carotid artery occlusion maintained by persistent embryologic collaterals: A case report. Radiology Case Reports, 21(7), 2791–2797.

26. Kowalewska, K. K., Pilawska, S. A., Łasocha, B., Kwinta, B., Popiela, T. J., Stachura, K., ... & Krzyżewski, R. M. (2025). Accessory middle cerebral artery, hypoplasia of the A1 segment of the left anterior cerebral artery, fenestration of the A2 segment of the left anterior cerebral artery and fetal variant of posterior cerebral artery. Surgical and Radiologic Anatomy, 47(1), 187.

27. Kubicki, C., Simon, S., & Manning, K. B. (2026). Computational fluid dynamics assessment of altered hemodynamics in the Circle of Willis during acute ischemic stroke and the impact of cerebral collateral development. Biomechanics and Modeling in Mechanobiology, 25(2), 28.

28. Lambert, S. L., Williams, F. J., Oganisyan, Z. Z., Branch, L. A., & Mader, E. C., Jr. (2016). Fetal-type variants of the posterior cerebral artery and concurrent infarction in the major arterial territories of the cerebral hemisphere. Journal of Investigative Medicine High Impact Case Reports, 4(3), 2324709616665409.

29. Laviv, Y., Thomas, A., & Kasper, E. M. (2017). Hypervascular lesions of the cerebellopontine angle: The relevance of angiography as a diagnostic and therapeutic tool and the role of stereotactic radiosurgery in management. World Neurosurgery, 100, 100–117.

30. Lengyel, B., Magyar-Stang, R., Pál, H., Debreczeni, R., Sándor, Á. D., Székely, A., ... & Mihály, Z. (2024). Non-invasive tools in perioperative stroke risk assessment for asymptomatic carotid artery stenosis with a focus on the Circle of Willis. Journal of Clinical Medicine, 13(9), 2487.

31. Liu, H., Wang, D., Leng, X., Zheng, D., Chen, F., Wong, L. K. S., ... & Leung, T. W. H. (2020). State-of-the-art computational models of Circle of Willis with physiological applications: A review. IEEE Access, 8, 156261–156273.

32. Lucifero, A. G., Baldoncini, M., Bruno, N., Tartaglia, N., Ambrosi, A., Marseglia, G. L., ... & Luzzi, S. (2021). Microsurgical neurovascular anatomy of the brain: The anterior circulation (Part I). Acta Bio Medica: Atenei Parmensis, 92(Suppl 4), e2021412.

33. Makowicz, G., Poniatowska, R., & Lusawa, M. (2013). Variants of cerebral arteries: Anterior circulation. Polish Journal of Radiology, 78(3), 42.

34. Maldonado, I. L., Dugast, E., & Destrieux, C. (2026). Basic anatomy of cerebral vessels. In Surgical and Interventional Treatment of Cerebral Ischemia: Basic Science to Clinical Practice (pp. 23–33). Springer Nature Switzerland.

35. Nas, E., Nteli Chatzioglou, G., & Gayretli, Ö. (2024). Anatomical evaluation of P1 segment of posterior cerebral artery and posterior

communicating artery in 340 human hemispheres: A proposal for morphological classification. Surgical and Radiologic Anatomy, 46(5), 685–695.

36. Ojha, V., Raju, S. N., Deshpande, A., Ganga, K. P., & Kumar, S. (2023). Catheters in vascular interventional radiology: An illustrated review. Diagnostic and Interventional Radiology, 29(1), 138.

37. Petridis, A. K., & Maslehaty, H. (2024). Vascular neurosurgery in environments with limited resources. Springer.

38. Qannas, A. S. M. A., Haffis, A. A. A., Abdelkader, A., Ekvtimishvili, E., Gaikwad, J., Tchikhoria, T., ... & Patil, C. (2026). Gender-based patterns in intracranial aneurysm site and rupture risk: A single-center retrospective cohort study from the Caucasus region. Artery Research, 32(1), 3.

39. Ren, Y., Chen, Q., & Li, Z. Y. (2015). A 3D numerical study of the collateral capacity of the Circle of Willis with anatomical variation in the posterior circulation. Biomedical Engineering Online, 14(Suppl 1), S11.

40. Ryu, J. C., & Kim, J. S. (2022). Mechanisms of stroke in patients with fetal posterior cerebral artery. Journal of Stroke and Cerebrovascular Diseases, 31(8), 106518.

41. Saha, A., Bhattacharya, A., & Mullick, A. (2026). Morphological evaluation of completeness of Circle of Willis. Anatomical Science International, 101(1), 54–60.

42. Salerno, A., Strambo, D., Nannoni, S., Dunet, V., & Michel, P. (2022). Patterns of ischemic posterior circulation strokes: A clinical, anatomical, and radiological review. International Journal of Stroke, 17(7), 714–722.

43. Schulte-Altedorneburg, G., & Becker, T. (2005). Extent of spontaneous cross-flow via the anterior communicating artery in steno-occlusive carotid artery disease. Neurological Research, 27(4), 441–445.

44. Seifert, K., & Heit, J. J. (2023). Collateral blood flow and ischemic core growth. Translational Stroke Research, 14(1), 13–21.

45. Shaban, S., Huasen, B., Haridas, A., Killingsworth, M., Worthington, J., Jabbour, P., & Bhaskar, S. M. M. (2022). Digital subtraction angiography in cerebrovascular disease: Current practice and perspectives on diagnosis, acute treatment and prognosis. Acta Neurologica Belgica, 122(3), 763–780.

46. Shen, Y., Molenberg, R., Bokkers, R. P., Wei, Y., Uyttenboogaart, M., & van Dijk, J. M. C. (2022). The role of hemodynamics through the Circle of Willis in the development of intracranial aneurysm: A systematic review of numerical models. Journal of Personalized Medicine, 12(6), 1008.

47. Songur, A., Gonul, Y., Ozen, O. A., Kucuker, H., Uzun, I., Bas, O., & Toktas, M. (2008). Variations in the intracranial vertebrobasilar system. Surgical and Radiologic Anatomy, 30(3), 257–264.

48. Tan, A., & Roberts, D. (2021). Cerebral circulation 1: Anatomy. BJA Education, 21(10), 390–395.

49. Triantafyllou, G., Melissanidis, S., Arkoudis, N. A., Papadopoulos-Manolarakis, P., Tsakotos, G., & Piagkou, M. (2026). A rare combination of anterior cerebral arterial ring with accessory middle and duplicated posterior cerebral arteries. Surgical and Radiologic Anatomy, 48(1), 67.

50. Triantafyllou, G., Papadopoulos-Manolarakis, P., Arkoudis, N. A., Velonakis, G., Samolis, A., Olewnik, Ł., ... & Piagkou, M. (2026). Considerations on the morphological variability of the posterior inferior cerebellar artery origin. Neuroradiology, 68(1), 287–296.

51. Vasović, L., Milenković, Z., & Pavlović, S. (2002). Comparative morphological variations and abnormalities of circles of Willis: A minireview including two personal cases. Neurosurgical Review, 25(4), 247–251.

52. Vasović, L. P., Jovanović, I. D., Ugrenović, S. Z., & Andjelković, Z. P. (2008). Normal subtypes of the posterior part of the cerebral arterial circle in human fetuses. Surgical Neurology, 70(3), 287–294.

53. Vilela, P., & Goulao, A. (2005). Ischemic stroke: Carotid and vertebral artery disease. European Radiology, 15(3), 427–433.

54. Wei, X., Jiang, J., Cao, W., Yu, H., Deng, H., Chen, J., ... & Zhou, Z. (2022). Artificial intelligence assistance improves the accuracy and efficiency of intracranial aneurysm detection with CT angiography. European Journal of Radiology, 149, 110169.

55. Wijesinghe, P., Steinbusch, H. W. M., Shankar, S. K., Yasha, T. C., & De Silva, K. R. D. (2020). Circle of Willis abnormalities and their clinical importance in ageing brains: A cadaveric anatomical and pathological study. Journal of Chemical Neuroanatomy, 106, 101772.

56. Zampakis, P., Panagiotopoulos, V., Petsas, T., & Kalogeropoulou, C. (2015). Common and uncommon intracranial arterial anatomic variations in multi-detector computed tomography angiography (MDCTA): What radiologists should be aware of. Insights into Imaging, 6(1), 33–42.

57. Zarrinkoob, L., Ambarki, K., Wåhlin, A., Birgander, R., Eklund, A., & Malm, J. (2015). Blood flow distribution in cerebral arteries. Journal of Cerebral Blood Flow & Metabolism, 35(4), 648–654.

58. Zeng, T. F., Zhu, G. S., Chen, B., Jiang, X. L., Li, S. Y., Huang, H. F., & Liu, J. (2026). Clipping

posteriorly directed posterior communicating artery aneurysms using the anterior temporal approach. World Neurosurgery, 205, 124749.

59. Zhang, P., Wang, Z., Yu, F. X., Lv, H., Liu, X. H., Feng, W. H., ... & Wang, Z. C. (2018). The clinical presentation and collateral pathway development of congenital absence of the internal carotid artery. Journal of Vascular Surgery, 68(4), 1054–1061